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Geothermal resource assessment in Korea

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ABSTRACT

To estimate available geothermal energy and to construct temperature at depth maps in Korea, various geothermal data have been used. Those include 1560 thermal property data such as thermal conductivity, specific heat and density, 353 heat flow data, 54 surface temperature data, and 180 heat production data. In Korea, subsurface temperature ranges from 23.9 °C to 47.9 °C at a depth of 1 km, from 34.2 °C to 79.7 °C at 2 km, from 44.2 °C to 110.9 °C at 3 km, from 53.8 °C to 141.5 °C at 4 km, and from 63.1 °C to 171.6 °C at 5 km. The total available subsurface geothermal energy in Korea is 4.25×10^{21} J from surface to a depth of 1 km, 1.67×10^{22} J to 2 km, 3.72×10^{22} J to 3 km, 6.52×10^{22} J to 4 km, and 1.01×10^{23} J to 5 km. In particular, the southeastern part of Korea shows high temperatures at depths and so does high geothermal energy. If only 2% of geothermal resource from surface to a depth of 5 km is developed in Korea, energy from geothermal resources would be equivalent to about 200 times annual consumption of primary energy ($\sim 2.33 \times 10^8$ TOE) in Korea in 2006.

Contents

1. Introduction

It is well known that Korea is an energy-deficient country. About 97 percent of the energy consumed is imported. Korea is now the world's fourth-largest energy importer [1]. Therefore, the country is extremely vulnerable to rises in oil prices, as it has to

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import all its crude oil needs and it has to reduce its oil use and meet tightening global standards on the environment. In Korea, there is no oil productivity and the coal industry has been declined. The hydroelectric potential has reached its limit in Korea. Since the early 1970s, Korea has developed nuclear energy. As of 2007, nuclear energy accounted for 35% of the total energy production in Korea [2]. However, there is growing concern about the consequences of the uses of nuclear energy. For example, long-term storage as well as disposal of radioactive wastes causes serious problems.

In the past century, it has been seen in many countries that the consumption of non-renewable sources of energy (e.g., crude oil, coal, nuclear energy and so on) has caused more environmental damage than any other human activity. Energy generated from fossil fuels such as coal and crude oil has led to increased concentration of greenhouse gases in the atmosphere. These gases, in turn, have led to many problems being faced today such as global warming. Therefore, many countries, including Korea, have focused on the development of renewable and clean energy sources. Geothermal energy source is one of them.

Geothermal energy originates from the Earth's deep interior and the decay of radioactive elements mainly in the upper crust. Using geothermal energy obviously can replace fossil fuel use and prevent the emission of greenhouse gases. In Korea, geothermal energy has been used for public bath ($\sim$40 °C to 70 °C) and balneology for about 1000 years up until modern times, and for space cooling and heating recently. In addition, geothermal development in the future will put greater emphases on enhanced geothermal system (EGS) in Korea.

To meet recent and future needs for sophisticated analyses of available geothermal resources, we have performed geothermal resource assessment in Korea to investigate the geothermal potential of the whole country for various geothermal applications including EGS.

Geothermal resource assessment is the estimation of the amount of thermal energy that might be extracted from the Earth and used economically at some reasonable future time. A resource assessment is regional or national in scope and thus provides a framework for long-term energy policy and strategy decisions by industry and government. Geothermal resource assessment has been done in many countries such as Brazil [3], Canada [4], China [5], Denmark [6], Germany [7], Mexico [8], Pakistan [9], Sweden [10], Switzerland [11,12], the Unite States [13–17], and so on.

Until now, no estimates exist for the potential upper limit to geothermal capacity in Korea. This study is the first systematic effort to assess and estimate the geothermal resources of Korea. If new sites with low and high enthalpy geothermal energy can be discovered and developed in Korea, it will be a major environmental and economical benefit because geothermal energy offsets air pollution and reduces Korea's dependency on crude oil.

2. Geology

Korea located in the continental margin of the eastern Eurasian continent is a composite landmass consisting of three tectonic blocks. From north to south, there are the Kyeonggi and Yeongnam massifs that are divided by Okcheon fold belt, and Gyeongsang sedimentary basin located in the southeastern part of Korea (Fig. 1). Rocks in Korea are composed of relatively old rocks such as Precambrian metamorphic rocks as basement rocks (e.g., gneiss and schist), Paleozoic and Mesozoic sedimentary rocks, Jurassic and Cretaceous granites, and some young volcanic rocks. Especially, Jurassic and Cretaceous granites, and Precambrian gneiss occupy about 50% of Korea. More detailed geological information of Korea is given by Lee [18] and Chough et al. [19].

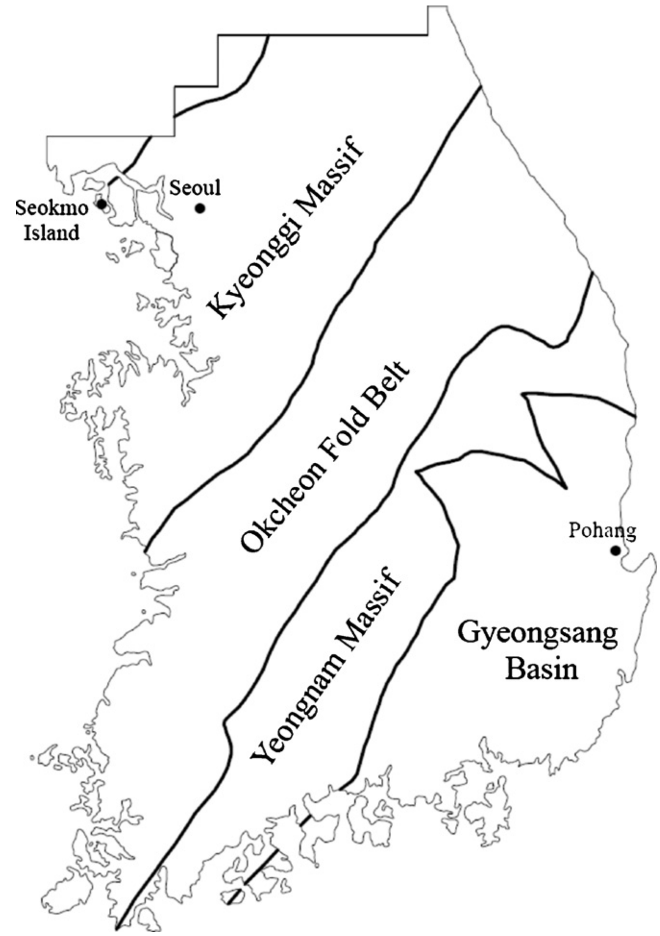

Fig. 1. Tectonic provinces in Korea.

3. Geothermal applications

Since about 1000 years ago, Koreans have used a number of hot springs for public bath and balneology. As of now, it is known that there exist 233 geothermal wells and 452 hot spring facilities in Korea, especially in areas of granites [20]. For modern applications, ground source heat pump systems for heating and cooling have been installed recently in many places in Korea. Those include closed systems with borehole heat exchangers (e.g., vertical or horizontal loop systems and so on) and groundwater heat pump systems (e.g., standing column well, aquifer thermal storage system and so on) using groundwater in shallow aquifers as the main carrier of the energy.

In 2000, two ground source heat pump systems (a total capacity of 35.2 kWt) were installed in Korea for the first time. Since then, the use of ground source heat pump systems has rapidly increased in Korea. As of August of 2008, a total of 551 buildings has been equipped with ground source heat pump systems for heating and cooling (a total capacity of 127.1 MWt) [20].

Recently, Jungwon University, established in 2009, has installed the large-scale ground source heat pump system (closed loop system) for heating and cooling. This system has 245 boreholes with a depth of 150 m; its total capacity is 13,512 kWt. The ground source heat pump system undertakes cooling and heating for 52% of the entire university building space.

For deeper geothermal applications, in 2003 Korea Institute of Geoscience and Mineral Resource (KIGAM) launched the first large-scale geothermal project for district heating ($\sim$75 °C) and greenhouse use ($\sim$45 °C) in Pohang city located in the southeastern

part of Korea with the highest geothermal gradient (~48 °C/km) and heat flow (~89 mW/m^2) in Korea (Fig. 1). In this project, four deep exploration wells have been drilled down to the depths of 1.0–2.3 km in Pohang city, and geological and geophysical surveys including well-logging have been carried out. KIGAM expects to extract 2000 tons/day of geothermal water with temperature higher than ~75 °C which is enough for the direct heating of about 1500 houses.

So far, geothermal power generation has not been realized in Korea. However, the sharp increase in energy prices, combined with Kyoto protocol measures and preferable government policy for renewable energy, leads to an increasing interest in geothermal power generation in Korea. In the early of 2009, KIGAM launched a large-scale geothermal project for power generation in Seokmo Island located in the west coast of Korea (Fig. 1). It is known that more than 25 hot spring wells have been drilled in that area. One of them produces 4000 tons/day geothermal water (~70 °C) at the depth of about 1.2 km. KIGAM will drill a borehole down to 3 km in Seokmo Island to investigate the thermal and hydrological state of that area and they expect to extract geothermal water with temperature of higher than ~90 °C at the depth of 3 km for geothermal power generation (>~200 kWe).

EGS is one of the most advanced geothermal applications for geothermal power generation. EGS is defined as engineered reservoirs that have been created to extract heat from economically unproductive geothermal resources. EGS concept is to extract heat by creating a subsurface fracture system to which water can be added through injection wells. The water is heated by contact with the rock and returns back to the surface through production wells, just as in naturally occurring hydrothermal systems. In Korea, EGS is currently a planning stage; some national institutes including KIGAM and national companies are now conducting feasibility studies on EGS in Korea. As EGS technology develops, it is likely that in the future, it will become of greater interest to Korea. Geothermal resource assessment will give crucial information on site selection for EGS in Korea.

As mentioned above, although currently at a very low level, the usage of geothermal energy in Korea is beginning to show an upward trend.

4. Theory

Heat content in an area can be estimated by different methods. Those include the volume method, the heat flux method, the planar fracture method, and the method of magmatic head budget [21]. Among them, we used the volume method that estimates energy contained within a certain volume of rock. The volume method is most commonly used for assessments of geothermal resources [13–15,21] and has been recently applied for geothermal resource assessment for the United States [16,17].

Heat content at depth can be estimated by the volume method as

$$Q = \rho C_p V \Delta T \quad (1)$$

where ρ is density, C_p is specific heat, V is volume of rock, and ΔT is the temperature difference between top and bottom of rock volume.

Table 1
Volume for different depth intervals.

Depth interval (km)	Volume (km^3)
0–1	99,469.2
0–2	198,938.3
0–3	298,407.5
0–4	397,876.6
0–5	497,345.8

Assuming radiogenic elements (U, Th, and K) decrease exponentially with increasing depth [22], the temperature at depth for a crystalline rock terrain can be expressed as

$$T(z) = \frac{A_o b^2}{K}(1 - e^{-z/b}) + \left(\frac{q_o - A_o b}{K}\right) z + T_o \quad (2)$$

where $T(z)$ is temperature at depth z, A_o is surface heat production, b is attenuation depth, K is thermal conductivity, q_o is surface heat flow, and T_o is surface temperature [16].

5. Geothermal data

Geothermal data including density, specific heat, thermal conductivity, heat flow, heat production, and surface temperature has been modeled using grid modeling software within a Geographic Information System (GIS). The GIS software used is ArcGIS. A grid is made up of regularly spaced square cells (500 m by 500 m) arranged over entire Korea.

5.1. Volume

The surface area of Korea is 99,469.2 km^2. Table 1 shows volume data from surface to different depths up to 5 km in Korea.

5.2. Thermal properties

A total 1560 of fresh outcrop samples were collected from entire Korea. For estimation of temperature at depths, thermal conductivity was assumed as being vertically homogeneous. Thermal conductivity (K) were estimated from thermal diffusivity (α), specific heat (C_p), and density (ρ) using the following relationship,

$$K = \alpha \rho C_p \quad (3)$$

Thermal diffusivity and specific heat of rock samples were measured by a LFA-447 Xenon flash lamp machine from Netzsch, which measures those thermal properties by monitoring the temperature increase of the sample caused by a pulse from the laser flash. A LFA-447 Xenon flash lamp machine was calibrated with a standard sample (pyroceram 9606) with thermal conductivity of 4.009 W/m K at 25 °C; the probable inaccuracy of thermal conductivity measurement due to instrument errors in a LFA-447 Xenon flash lamp machine is no greater than ±7%. Density of samples was measured by a gas displacement technique instrument, AccuPyc 1330 Pycnometer from Micromeritics Instrument Corporation.

A summary of various thermal properties for geothermal resource assessment is included on Table 2. Specific heat ranges from 523.0 J/kg K to 1181.0 J/kg K with a mean of 856.8 J/kg K

Table 2
Summary of thermal property data used for geothermal resource assessment.

	A_0 (μW/m^3)	C_p (J/kg K)	K (W/m K)	q_0 (mW/m^2)	T_0 (°C)	ρ (kg/m^3)
Mean	2.04	856.8	3.54	65.2	14.4	2673.7
Range value	0.18–5.70	523.0–1181.0	1.60–8.76	35.2–102.3	8.6–16.7	1883.2–3182.2
Number of data	180	1560	1560	353	54	1560

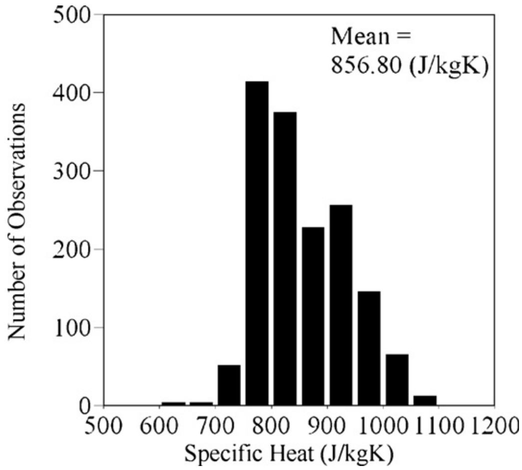

Fig. 2. Histogram of specific heat data from 1560 samples.

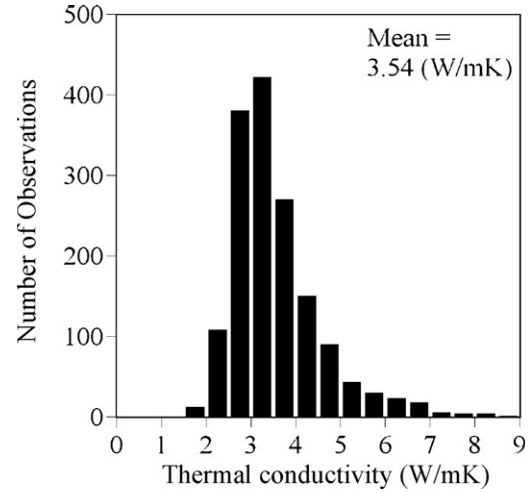

Fig. 4. Histogram of thermal conductivity data from 1560 samples.

(Figs. 2 and 3; Table 2); thermal conductivity ranges from 1.60 W/m K to 8.76 W/m K with a mean of 3.54 W/m K (Figs. 4 and 5; Table 2); density ranges from 1883.2 kg/m^3 to 3182.2 kg/m^3 with a mean of 2673.7 kg/m^3 (Figs. 6 and 7; Table 2). Granites and metamorphic rocks occurred in the middle and the northern part of Korea have relatively high specific heat, thermal conductivity, and density (Figs. 3, 5 and 7), while sedimentary rocks occurred in the southeastern part of Korea have relatively low specific heat, thermal conductivity, and density (Figs. 4, 5 and 7).

5.3. Heat flow

Kim and Lee [23] reported a total of 359 heat flow data from Korea. In this study, 353 heat flow data compiled by Kim and Lee [23] is used for geothermal resource assessment (Fig. 8). For heat flow estimation, geothermal gradient data were measured in the boreholes of mainly mines, coal fields, hot springs, and groundwater wells; thermal conductivities were measured on core samples or fresh outcrops by the Schröder's method, a quick thermal conductivity meter (QTM), or a laser flash machine. The mean geothermal gradient of the Korea is 25.1 °C/km; mean heat flow of Korea is 65 mW/m^2 [23]. The southeastern part, the central western part, and the northeastern part of Korea show high geothermal gradients and high heat flow values (Fig. 9).

5.4. Heat production

A total of 180 heat production values were estimated on basement rocks (granite and gneiss) by chemical analysis and from gamma-ray logs. Among 180 heat production data, a total of 125

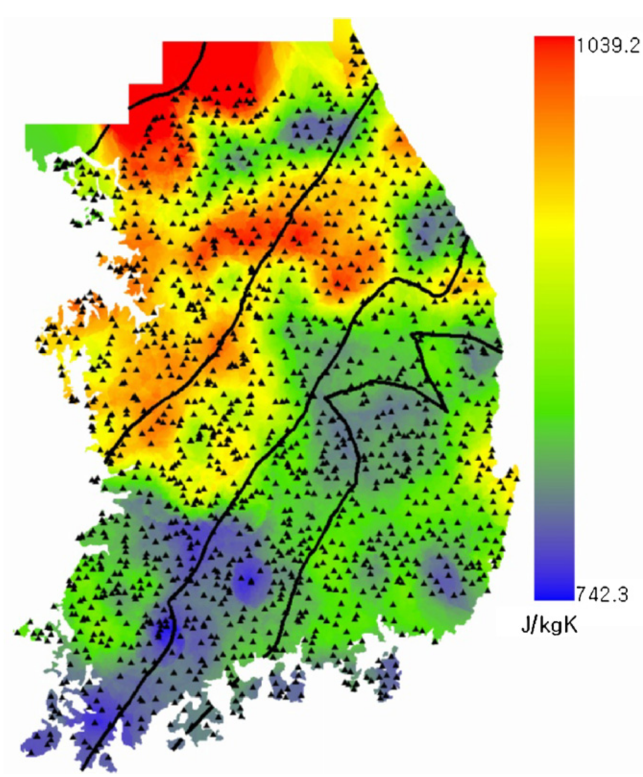

Fig. 3. Contour map of specific heat in Korea from 1560 data.

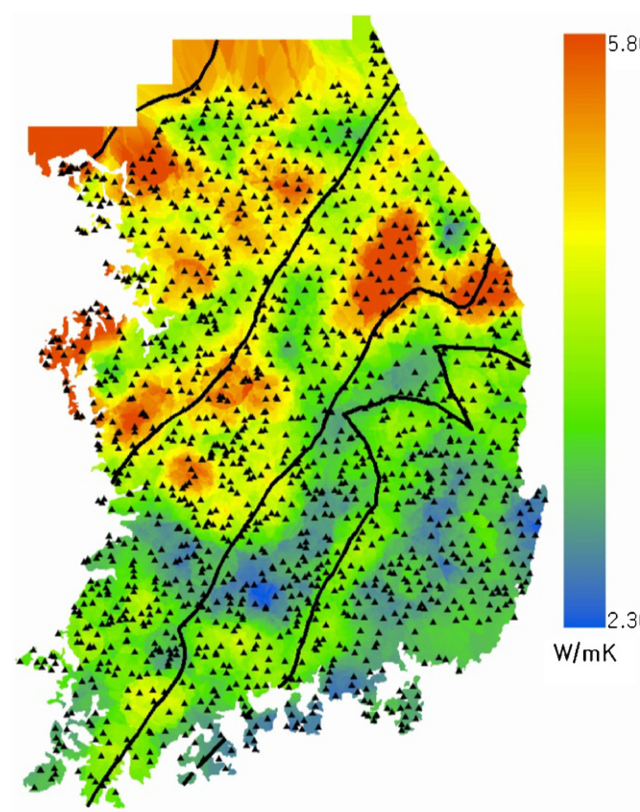

Fig. 5. Contour map of thermal conductivity in Korea from 1560 data.

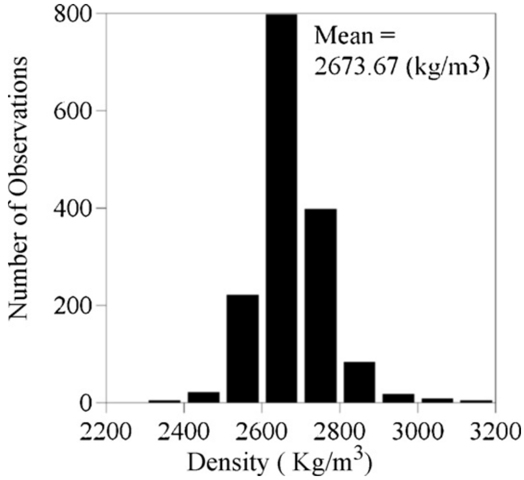

Fig. 6. Histogram of density data from 1560 samples.

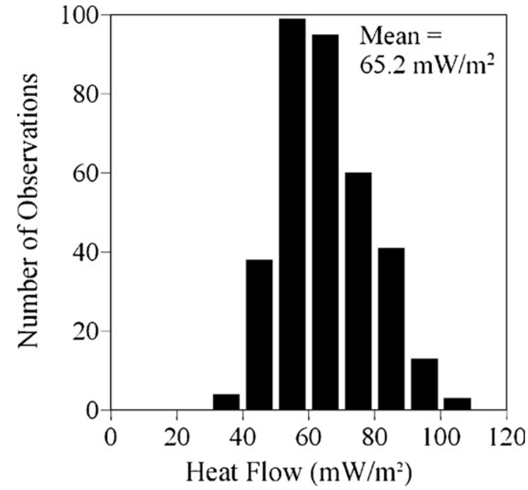

Fig. 8. Histogram of heat flow data from 180 data.

heat production data were estimated by chemical analysis, while a total of 55 heat production data were estimated from gamma-ray logs. For chemical analysis, the amount of U and Th was determined by inductively coupled-plasma mass spectrometry (ICP-MS); the amount of *K* was determined by atomic absorption spectrometer (AAS). Finally, heat generation was estimated by an empirical equation by Rybach [24] as

$$A = 10^{-5}\rho(9.52\mathrm{U} + 2.56\mathrm{Th} + 3.48\mathrm{K}) \quad (4)$$

where ρ is density of the rock in kg/m^3, U and Th are the contents of uranium and thorium in ppm, and K is the content of potassium in wt.%.

In addition, a total of 55 heat production values were estimated by gamma-ray logs using an empirical relationship introduced by Bücker and Rybach [25] as

$$A = 0.0158(\gamma - 0.8) \quad (5)$$

where A is heat production in μW/m^3 and γ is the gamma-ray log reading in API units. Bücker and Rybach's equation [25] is known to be accurate to within 10% for $0.03 \leq A \leq 7.0\ \mu\mathrm{W/m^3}$.

The mean of heat production is 2.040 μW/m^3 for granite samples and 2.041 μW/m^3 for gneiss samples. Heat production for entire data ranges from 0.18 μW/m^3 to 5.70 μW/m^3 with a mean of 2.040 μW/m^3 (Figs. 10 and 11; Table 2). Gyeongsang sedimentary basin located in the southeastern part of Korea has relatively low heat production (Fig. 11).

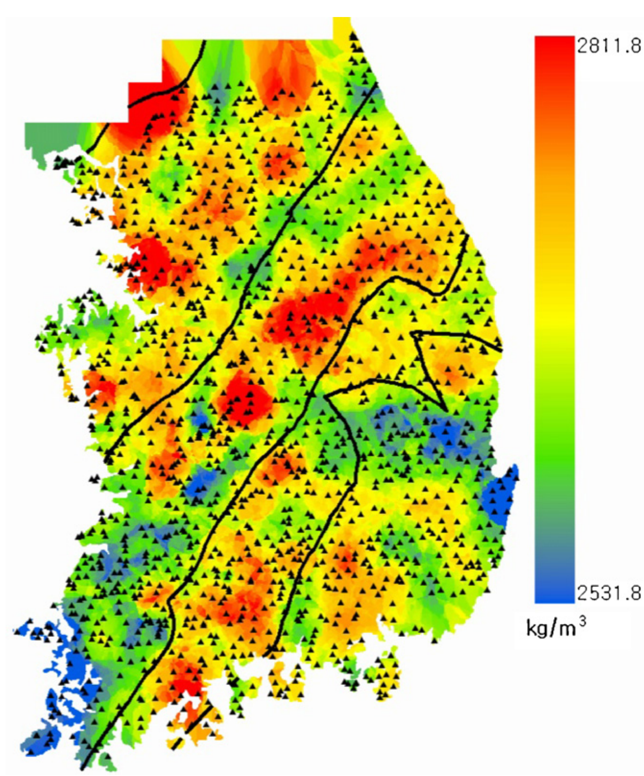

Fig. 7. Contour map of density in Korea from 1560 data.

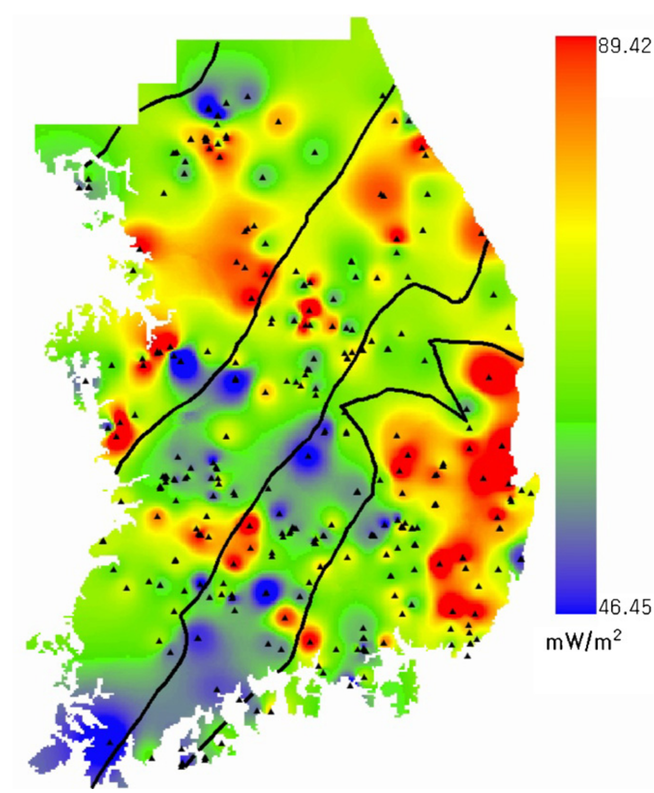

Fig. 9. Contour map of heat flow in Korea from 353 data.

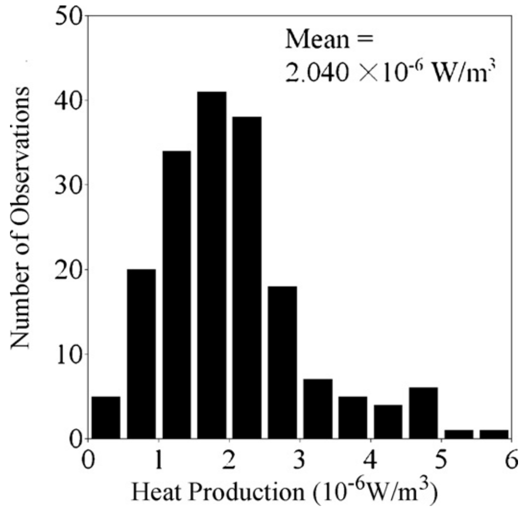

Fig. 10. Histogram of heat production data from 180 samples.

5.5. Surface temperature

Korean Meteorological Administration (KMA) has measured ground surface temperatures (GSTs), surface air temperatures (SATs), and other important meteorological parameters in Korea since the early of 20 century. Especially, KMA has been measured GSTs at the depths of 0–5 m with sampling intervals of 6 h for the depths shallower than 0.3 m and 24 h for deeper ones.

Koo et al. [26] collected GSTs that have been measured and digitally recorded at 58 KMA stations from 1981 to 2002. Then, they estimated the mean GST for each station using an arithmetic mean after data adjustment that includes removing erroneous data. Detailed data adjustment procedure is given in Koo et al. [26].

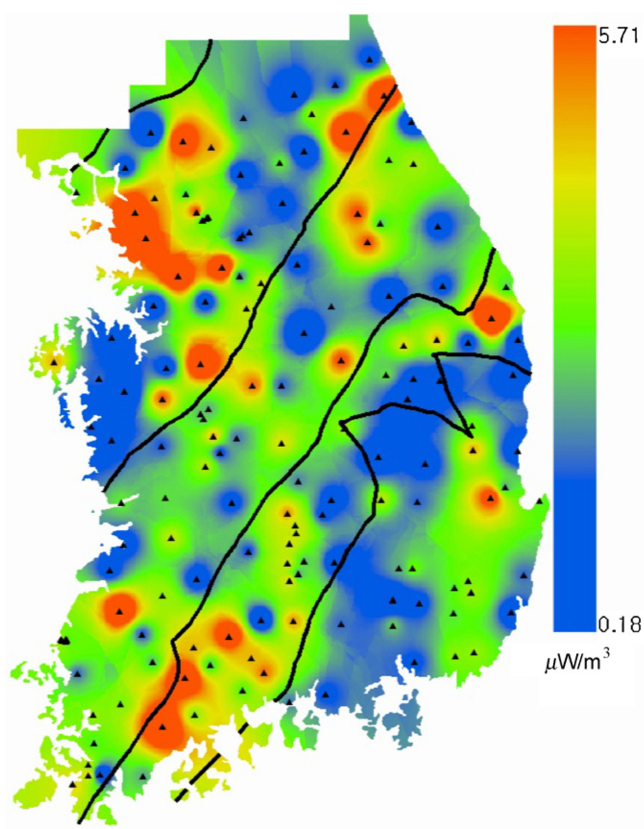

Fig. 11. Contour map of heat production in Korea from 180 data.

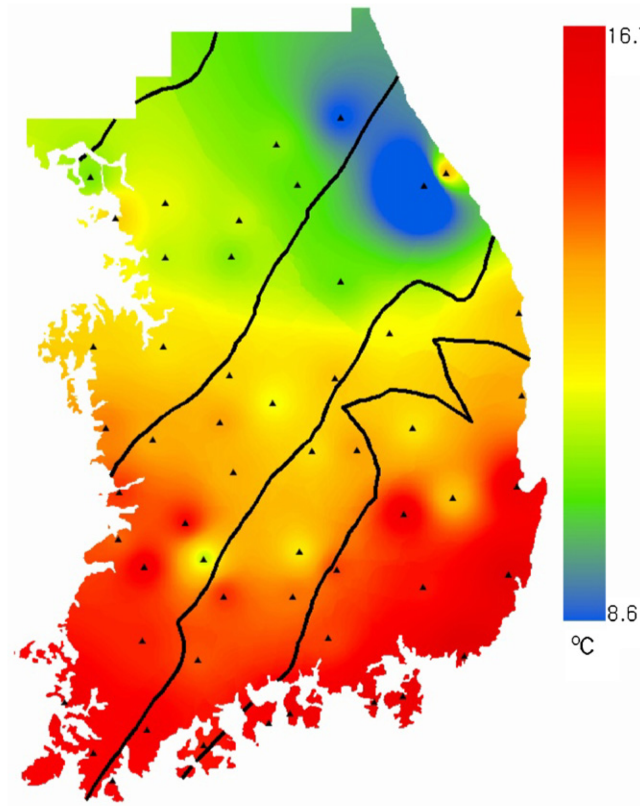

Fig. 12. Contour map of surface temperature in Korea from 54 data.

The GST contour map using GSTs of 58 KMA stations is shown in Fig. 12. In KMA data set, the lowest GST of 8.58 °C is measured at Daegwallyeong (842 m above sea level) located in Taebaek mountains, while the highest GST of 18.31 °C is observed at Seogwipo (51.0 m above sea level), Jeju island. The mean of measured GST contouring area is 13.9 °C (Fig. 12).

6. Results

6.1. Temperature at depths

Temperatures were estimated from the depths of 1–5 km at every km. The contour maps of the temperatures are shown in Fig. 13. The accuracy of temperature estimations at depths could not be checked directly because there are no deep boreholes in Korea. However, Blackwell et al. [16] found that agreement between measured and estimated temperatures in the 3–6 km depth range in the Unite States is within ±20 °C.

In Korea, subsurface temperature ranges from 23.9 °C to 47.9 °C at a depth of 1 km, from 34.2 °C to 79.7 °C at 2 km, from 44.2 °C to 110.9 °C at 3 km, from 53.8 °C to 141.5 °C at 4 km, and from 63.1 °C to 171.6 °C at 5 km (Fig. 13). Some similar patterns of warmer temperatures as seen at 1 km are also seen at different depths (2–5 km) (Fig. 13). This result indicates that some areas in the southeastern part of Korea show temperature higher than 150 °C at a depth of 5 km (Fig. 13f). These areas would satisfy the minimum temperature requirement for EGS.

6.2. Heat content

The total available subsurface geothermal energy in Korea is 4.25×10^{21} J from surface to a depth of 1 km, 1.67×10^{22} J to 2 km, 3.72×10^{22} J to 3 km, 6.52×10^{22} J to 4 km, and 1.01×10^{23} J to 5 km (Fig. 14; Table 3). In particular, the southeastern part of Korea

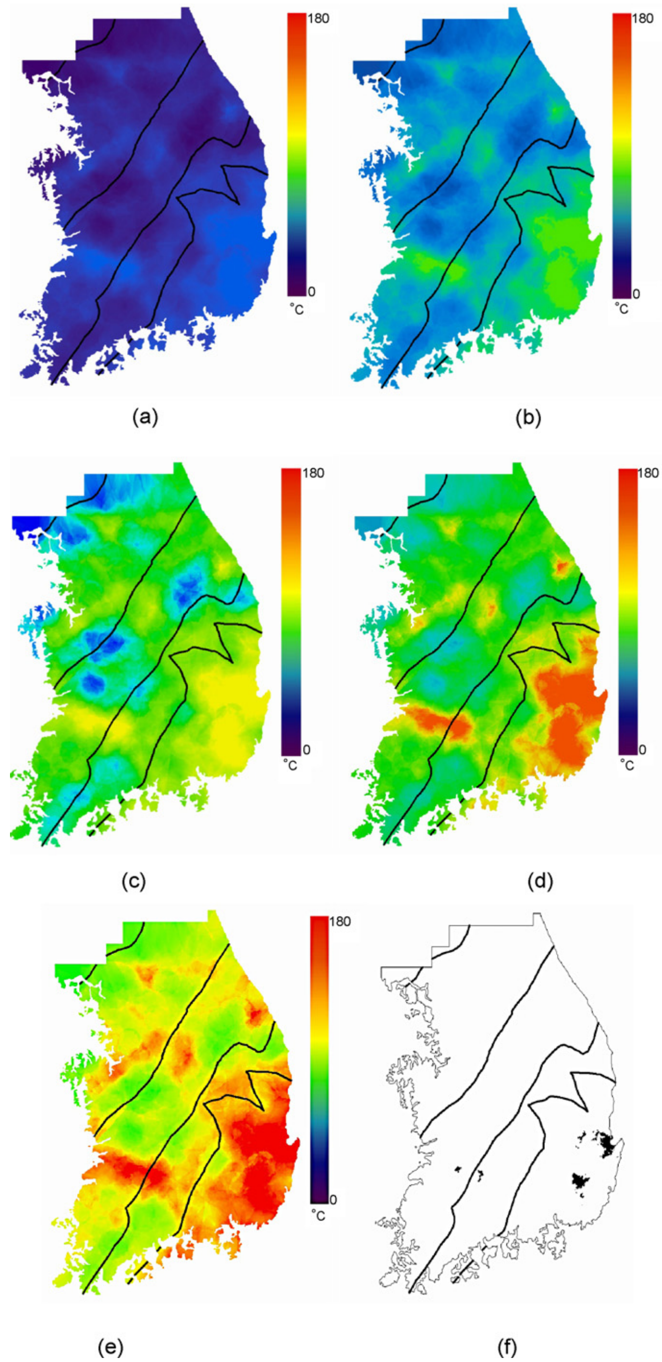

Fig. 13. Temperature at (a) 1 km, (b) 2 km, (c) 3 km, (d) 4 km, and (e) 5 km. (f) Areas with temperature higher than 150 °C at 5 km.

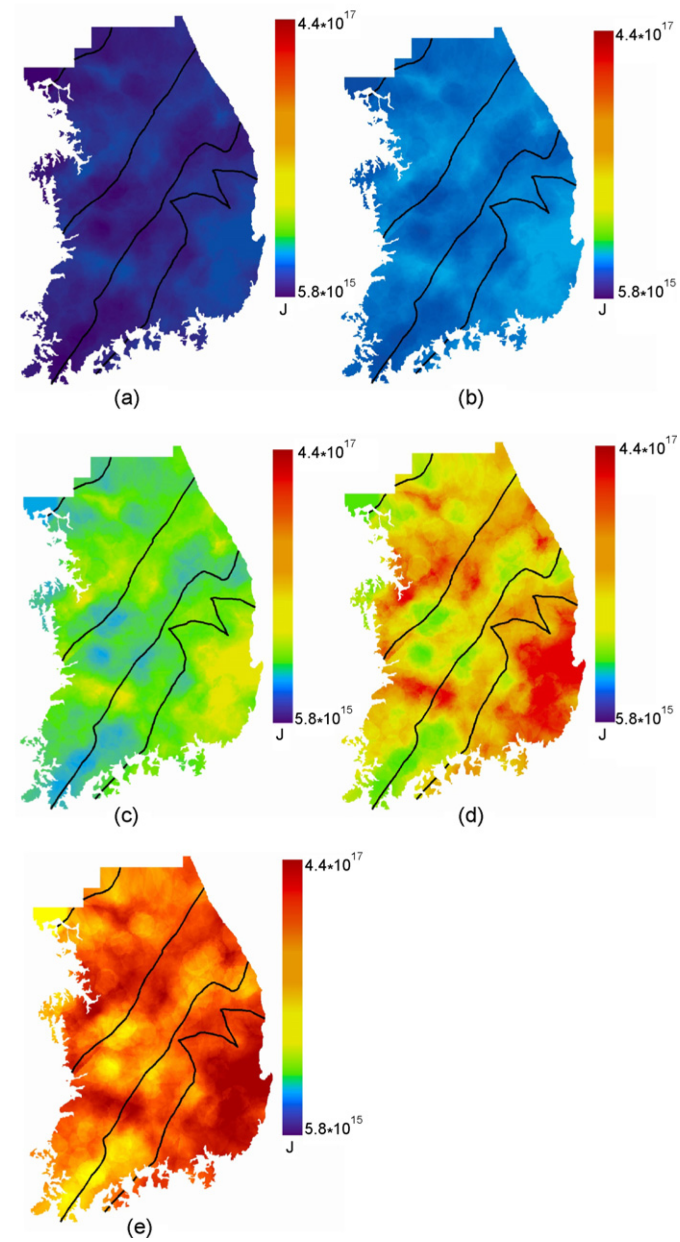

Fig. 14. Heat content (a) from surface to 1 km, (b) to 2 km, (c) to 3 km, (d) to 4 km, and (e) to 5 km.

shows high geothermal energy (Fig. 14). In terms of tectonic province, Gyeongsang basin has more geothermal energy per unit area than any other tectonic provinces in Korea (Table 4). The result indicates the enormous amount of energy stored in subsurface in Korea. If only 2% of geothermal resource from surface to a depth of 5 km is developed in Korea, energy from geothermal resources would be equivalent to about 200 times annual consumption of primary energy ($\sim$2.33 $\times$ 10^8 TOE) in Korea in 2006.

Table 3
Heat content for different depth intervals.

Depth interval (km)	Heat content in J	Heat content in GToe	Heat content in GToe (2%)
0–1	4.25×10^{21}	101.1	2.0
0–2	1.67×10^{22}	398.7	8.0
0–3	3.72×10^{22}	884.9	17.7
0–4	6.52×10^{22}	1552.8	31.1
0–5	1.01×10^{23}	2396.0	47.9

7. Discussion

7.1. Uncertainty due to thermal conductivity

In the estimation of temperature at depths using Eq. (2), we assumed that thermal conductivity is vertically homogeneous within 500 m by 500 m grid area. However, actually vertical distribution of thermal conductivity is heterogeneous, which causes some errors in the estimation of temperatures at depths, so does in the estimation of heat content. We examine uncertainty due to vertically homogeneous thermal conductivity in estimation

Table 4
Heat content from surface to 5 km for tectonic provinces.

	Area (km^2)	Heat content (J)	Heat content per unit area (J/km^2)
Gyeonggi massif	26,671.03	2.64×10^{22}	9.90×10^{17}
Okcheon fold belt	31,870.30	3.07×10^{22}	9.64×10^{17}
Yeongnam massif	18,082.62	1.70×10^{22}	9.41×10^{17}
Gyeongsang basin	21,028.43	2.52×10^{22}	1.20×10^{18}

Table 5
Mean values of thermal property data.

	A_0 ($\mu W/m^3$)	A_s ($\mu W/m^3$)	K (W/m K)	q_0 (mW/m^2)	T_0 (°C)	b (km)
Mean	1.74	1.41	3.07	71.1	15.1	12

of temperatures at depths and heat content using two end members (2.36 W/m K as minimum thermal conductivity and 5.86 W/m K as maximum thermal conductivity). In this test, Korea's average values of density, specific heat values, surface heat flow, heat production, and surface temperature are used for testing of uncertainty (Table 2). Table 6 shows that temperature at 5 km varies from 93.02 °C for 2.36 W/m K to 117.86 °C for 5.86 W/m K, and heat content from surface to 5 km varies from 2.67×10^{22} J for 2.36 W/m K to 3.38×10^{22} J for 5.86 W/m K. There may be considerable uncertainty due to homogenous thermal conductivity used in temperature estimates.

7.2. Uncertainty due to porosity

Heat content of water in pore space of rocks must take account of the estimation of heat content as Eq. (6)

$$Q = [(1 - \phi)\rho_m C_m + \phi \rho_w C_w] V (T_z - T_o) \quad (6)$$

where Q is heat content, ϕ is porosity, ρ_m is density of rock, C_m is specific heat of rock, ρ_w is density of water, C_w is specific heat of water, V is volume of rock, T_o is surface temperature, and T_z is temperature at depth.

In this study, porosity effect on heat content was ignored because porosity effect is probably negligible if porosity is small. The average porosity value of 1560 rocks samples from Korea is about 0.02 [27]. Heat content from surface to 5 km is 9.96×10^{22} J when porosity effect is included as Eq. (6), while heat content for the same interval is 9.80×10^{22} J when porosity effect is not included as Eq. (1). Therefore, porosity effect for the estimation of heat content is likely to be negligible in Korea.

7.3. Uncertainty due to sedimentary rock

In Korea, some areas are covered by sedimentary rocks (e.g., Gyeongsang basin) overlaying crystalline basement rocks, but, in this study, temperatures at depths in the sedimentary rock areas were estimated as those in the crystalline rock areas using Eq. (2) because the boundary between sedimentary rocks and crystalline basement rocks is not known in many locations at this moment. That may cause error in estimation of temperatures at depths

Table 6
Temperature at 5 km and heat content from surface to 5 km for different thermal conductivity values.

	K (W/m K)	T_z (°C)	Q (J)
Min. value	2.36	93.02	2.67×10^{22}
Ave. value	3.58	103.68	2.97×10^{22}
Max. value	5.86	117.86	3.38×10^{22}

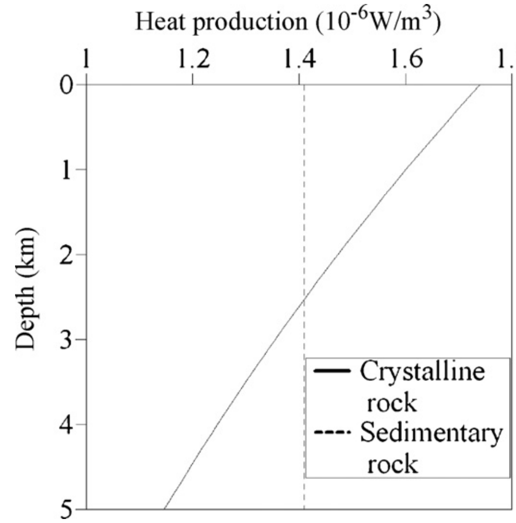

Fig. 15. Vertical distribution of heat production in crystalline rock and sedimentary rock in Korea.

because heat production value in sedimentary rock areas tends to be a linear with increasing depth, while heat production value in crystalline rock areas is known to be exponentially decreasing with increasing depth. We estimate possible uncertainty caused by vertical heat production distribution in sedimentary rock areas.

Assuming that Gyeongsang basin is entirely filled with sedimentary rocks from surface to 5 km, we compared temperatures at 5 km and heat content from surface to 5 km by the heat production distribution in sedimentary rock areas (linear model) with those by the heat production distribution in crystalline rock areas (exponential model) as mentioned above.

Because heat production tends to be a constant with increasing depth in sedimentary rock areas, temperatures at depths can be estimated as [16]

$$T_z = \frac{q_o z}{K} - A_s \frac{z^2}{2K} + T_o \quad (7)$$

where T_s is surface temperature, q_o is surface hear flow, z is depth, K is thermal conductivity, A_s is surface heat production, and T_o is surface temperature.

To compare temperature at 5 km and heat content from surface to 5 km for using a linear model (Eq. (7)) and for an exponential model (Eq. (2)), the average values of surface temperature, surface

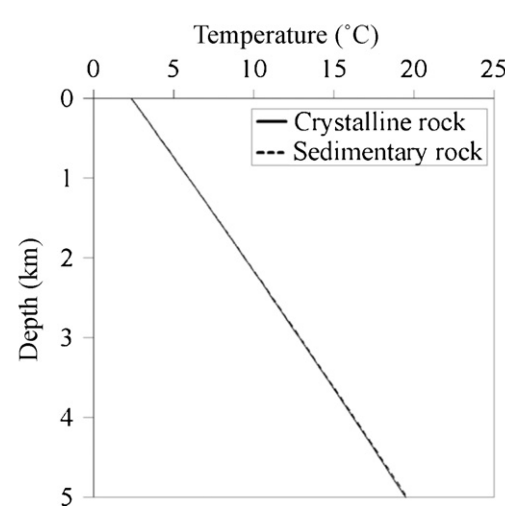

Fig. 16. Comparison of vertical temperature distribution in crystalline rock and sedimentary rock in Gyeongsang basin.

Table 7
Temperature at 5 km and heat content from surface to 5 km for different rock types in Gyeongsang basin.

	Temperature at 5 km (°C)	Heat content at 5 km (J)	Heat content at 5 km (J/km^2)
Crystalline rock	124.702	6.28×10^{21}	2.99×10^{17}
Sedimentary rock	125.157	6.31×10^{21}	3.00×10^{17}

heat flow, and thermal conductivity are used (Table 5). In addition, the average sedimentary rock heat production value of 1.41 μW/m^3 from the west-central part of Korea and the average crystalline basement rock heat production value of 1.74 μW/m^3 from Gyeongsang basin are used to estimate temperature at 5 km and heat content in Gyeongsang basin using a linear model (Eq. (7)) and a exponential model (Eq. (2)) (Fig. 15). As the result, temperature at 5 km reaches 125.2 °C from Eq. (7), while that reaches 124.7 °C at 5 km from Eq. (2) (Fig. 16); heat content from surface to 5 km in Gyeongsang basin is 6.31×10^{21} J for a linear model and 6.28×10^{21} J for an exponential model (Table 7). Although we used the exponential model for sedimentary rock areas because the boundary between sedimentary rock and crystalline basement rock is unknown, uncertainty in temperature at depth and heat content may be insignificant in Korea.

8. Conclusions

In Korea, subsurface temperature ranges from 23.9 °C to 47.9 °C at a depth of 1 km, from 34.2 °C to 79.7 °C at 2 km, from 44.2 °C to 110.9 °C at 3 km, from 53.8 °C to 141.5 °C at 4 km, and from 63.1 °C to 171.6 °C at 5 km. The total available subsurface geothermal energy in Korea is 4.25×10^{21} J from surface to a depth of 1 km, 1.67×10^{22} J to 2 km, 3.72×10^{22} J to 3 km, 6.52×10^{22} J to 4 km, and 1.01×10^{23} J to 5 km. Even though there may be considerable uncertainty in estimating subsurface temperature and geothermal energy, it is clear that there is substantial geothermal potential in Korea. In particular, the southeastern part of Korea shows high temperatures at depths and so does high geothermal energy. Therefore, deep sedimentary rock, as found in the southeastern part of Korea, is critical in the search for deep geothermal resources.

Because this geothermal resource assessment has been conducted in national scale, additional data in a specific area is required to confirm potential for deep geothermal applications including EGS before any deep drilling for exploitation is attempted.

While the entire resources cannot be recovered, the recovery of even a very small percentage of geothermal energy would make a large difference to the Korea's energy supplies. If only 2% of geothermal resource from surface to a depth of 5 km is developed in Korea, energy from geothermal resources would be equivalent to about 200 times annual consumption of primary energy ($\sim 2.33 \times 10^8$ TOE) in Korea in 2006.

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